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13. ABSTRACT *(Maximum 200 words)*

We investigate, theoretically and experimentally, ways to generate quantum mechanically correlated states between ensembles of atomic particles. The theoretical goals are: determine the best correlated states for particular applications and devise ways to generate these states and ways to measure them. The experimental goals are: demonstrate the increase in signal-to-noise ratio in spectroscopy using correlated particles, and apply stimulated Raman transitions for generation of the correlated states on transitions of general interest including microwave and optical transitions.
Results: We have written (theoretical) reports on the creation and detection of entangled states which give the maximum signal-to-noise ratio possible in spectroscopy. We have applied these results to particle (photon and atom) interferometers, showing which states and measurement strategy gives the Heisenberg uncertainty limit independent of the number of particles and phase difference between interferometer arms. Experimentally, we have been able to create quantum mechanical states which are entangled between a trapped ion's internal and motional states using stimulated-Raman transitions. For example, we have created a "Schrödinger-cat" type of state where the atom's position is correlated with its internal state. We have developed "tomographic" techniques for the complete characterization of motional states of trapped particles. We are in the process of developing microscopic linear rf traps for creating correlated states on strings of many ions.

14. SUBJECT TERMS
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QUANTUM MEASUREMENT WITH CORRELATED ATOMS

Final Report

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September 26, 1997

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A. STATEMENT OF THE PROBLEM STUDIED

We investigate, theoretically and experimentally, ways to generate quantum mechanically correlated states between ensembles of atomic particles. The theoretical goals are: determine the best correlated states for particular applications and devise ways to generate these states and ways to measure them. The experimental goals are: demonstrate the increase in signal-to-noise ratio in spectroscopy using correlated particles, and apply stimulated Raman transitions for generation of the correlated states on transitions of general interest including microwave and optical transitions.

Specific goals:

Theoretical - address four questions: (1) what, in principle, are the best correlated states for a particular application and (2) what are the generators, or interaction Hamiltonians, which, in practice, can produce the desired states, (3) what is the best measurement strategy to use on the correlated states, and (4) what are the fundamental and practical applications in addition to those that have already been identified (e.g., spectroscopy and interferometry).

Experimental - (1) demonstrate the increase in signal-to-noise ratio in electron spin resonance using correlated particles, and (2) apply stimulated Raman transitions for generation of the correlated states on transitions of general interest including microwave and optical transitions.

B. SUMMARY OF THE MOST IMPORTANT RESULTS

B.1 Spectroscopy and Interferometers

We have been able to show (theoretically) that the maximally entangled state

$$\Psi = \frac{1}{\sqrt{2}}\left(|\downarrow\rangle_1|\downarrow\rangle_2 ... |\downarrow\rangle_N + e^{i\phi}|\uparrow\rangle_1|\uparrow\rangle_2 ... |\uparrow\rangle_N\right), \tag{1}$$

gives the maximum signal-to-noise ratio in spectroscopy. Here, we consider an ensemble of N two-level atoms (lower and upper states of the ith atom designated by $|\downarrow\rangle_i$ and $|\uparrow\rangle_i$). We apply classical fields (Ramsey method with pulses separated in time by T_R) to this correlated state and achieve a frequency uncertainty given by $(\Delta\omega)_{meas.} = 1/(N^2T_R\tau)^{1/2}$ where τ is the total averaging time. This is to be compared to the expression $(\Delta\omega)_{meas.} = 1/(NT_R\tau)^{1/2}$ for uncorrelated particles. For an atomic clock where T_R is fixed by other constraints, this means that the time required to reach a certain measurement precision (stability) is reduced by a factor of N relative to the uncorrelated-atom case. This is important since very long averaging times (>> weeks) are used to achieve high precision in atomic clocks. This result also applies to particle (e.g., photon or atom) interferometers. The interferometer input state which is the analog of that in Eq. (1) is

$$\Psi = \frac{1}{\sqrt{2}}\left(|N\rangle_a|0\rangle_b + e^{i\phi}|0\rangle_a|N\rangle_b\right), \tag{2}$$

where the subscripts a and b denote the separate input ports to the interferometer. This entangled input state achieves the Heisenberg sensitivity limit independent of the number of particles and gives the maximum signal-to-noise ratio possible in an interferometer. This is the first time it has been shown that this state has this property.

B.2 Quantum logic and entanglement

We have experimentally demonstrated the first quantum logic gate with controlled input states. We have realized a "controlled-not" logic gate whose logic is given by

$$|\epsilon_1\rangle|\epsilon_2\rangle \rightarrow |\epsilon_1\rangle|\epsilon_1 \oplus \epsilon_2\rangle . \tag{3}$$

In this expression $\epsilon_1,\epsilon_2 \in \{0,1\}$ and $\oplus$ is addition modulo 2. The (implicit) phase factor in the transformation is equal to 1. In this expression ϵ_1 is the called the control bit and ϵ_2 is the target bit. If $\epsilon_1 = 0$, the target bit remains unchanged; if $\epsilon_1 = 1$, the target bit flips. In the single-ion experiment of Ref. 3 below, the control bit is the quantized state of one mode of the ion's motion. If the motional state is $|n=0\rangle$, it is taken to be a $|\epsilon_1=0\rangle$ state; if the motional state is $|n=1\rangle$, it is taken to be a $|\epsilon_1=1\rangle$ state. The target states are two ground-hyperfine states of the ion. Although "conditional dynamics," which is required to make a quantum gate, has been observed in experiments on cavity-QED (namely the groups of Haroche, Paris and Kimble, Cal Tech), the distinguishing feature of our work is that we are able to coherently prepare arbitrary input states, including arbitrary (entangled) superpositions of these states. That is, we have demonstrated the required "keyboard" for the input states. This logic gate is important to the creation of the maximally entangled states shown in Eqs. (1) and (2) since it can be shown that these states can be created with the application of N controlled-not gates to N ions.

B.3 Generation and characterization of nonclassical states of motion

We have concentrated on the creation and characterization of quantum states which are entangled between two internal states of a trapped atom and its motional states (in 1 dimension). Such studies are important because the entanglement operations between motional and internal states are a crucial prerequisite to creation of entanglement between many ions' internal states and also because these states are a sensitive indicator of decoherence in the problem. A particularly interesting entangled state is a "Schrödinger-cat" state.

A Schrödinger-cat state can be taken to be a coherent superposition of classical-like motional states. In Schrödinger's original thought experiment, he described how one could, in principle, entangle a superposition state of an atom with a macroscopic-scale superposition of a live and dead cat. In our experiment [Ref. 10 below], we construct an analogous state, on a smaller scale, with a single atom. We create the state

$$\Psi = \frac{1}{\sqrt{2}}(|\downarrow\rangle|\alpha_1\rangle + e^{i\phi}|\uparrow\rangle|\alpha_2\rangle) , \tag{4}$$

where $|\alpha_1\rangle$ and $|\alpha_2\rangle$ are coherent motional states, $|\uparrow\rangle$ and $|\downarrow\rangle$ denote the internal states of the atom, and ϕ is a (controlled) phase factor. The coherent states of the superposition are spatially separated by distances much greater than the (wave packet) size of the atom.

Analysis of this state is interesting from the point of view of the quantum measurement problem, an issue that has been debated since the inception of quantum theory by Einstein, Bohr, and others, and continues today. One practical approach toward resolving this controversy is the introduction of quantum decoherence, or the environmentally induced reduction of quantum superpositions into classical statistical mixtures [Zurek]. Decoherence provides a way to quantify the elusive boundary between classical and quantum worlds, and almost always precludes the existence of macroscopic Schrödinger-cat states, except for extremely short times. On the other hand, the creation of mesoscopic Schrödinger-cat states like that of Eq. (4) may allow controlled studies of quantum decoherence and the quantum-classical boundary. This problem

is directly relevant to the creation of correlated states between atoms.

In our experiment, we create a Schrödinger-cat state of the single-ion $^9Be^+$ harmonic oscillator with a sequence of laser pulses. First, we create a state of the form $(|\downarrow\rangle + e^{i\xi}|\uparrow\rangle)|n{=}0\rangle/\sqrt{2}$ with a "$\pi/2$ pulse" on the internal states. To spatially separate the $|\downarrow\rangle$ and $|\uparrow\rangle$ components of the wave function, we apply a coherent excitation with an optical dipole force which, because of the polarization of the beams used to create the force, selectively excites the motion of only the $|\uparrow\rangle$ state. We then swap the $|\downarrow\rangle$ and $|\uparrow\rangle$ states with an internal state π pulse and reapply the dipole force with a different phase to create the state of Eq. (4). In principle, if we could make $|\alpha_{1,2}|$ large enough, we could design a detector which could directly detect the (distinguishable) position of the particle and correlate it with a spin measurement. Instead, to analyze this state in our experiment, we apply an additional laser pulse to couple the internal states, and we measure the resulting interference of the distinct wavepackets. With this interferometer, we can establish the entanglement inherent in Eq. (4), the separation of the wavepackets, and the phase coherence ϕ between components of the wavefunction. These experiments are described in Ref.10. The interference signal is very sensitive to decoherence. As the separation $|\alpha_1 - \alpha_2|$ is made larger, decoherence is expected to exponentially degrade the fringe contrast.

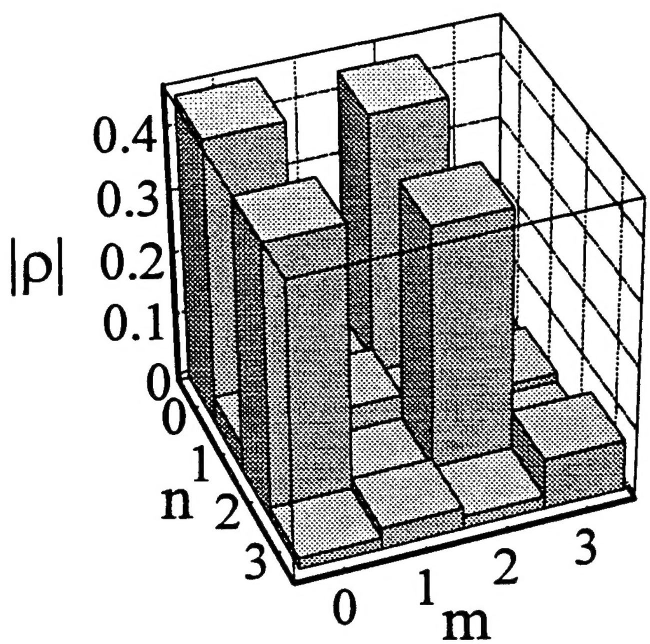

Fig. 1. Reconstructed density matrix amplitudes of an approximate $(|n{=}0\rangle - i\,|n{=}2\rangle)/\sqrt{2}$ state. The amplitudes of the coherences indicate that the reconstructed density matrix is close to that of a pure state.

The controlled interaction of light and rf-electromagnetic fields with the trapped ion not only allows us to prepare very general states of motion [as reported in Ref. 7 below], but also to determine these quantum mechanical states using novel techniques. Few experiments have succeeded in determining the density matrices or Wigner functions of quantum systems. In Ref. 13, we presented the theory and experimental demonstration of two distinct schemes to reconstruct both the density matrix in the number state basis and the Wigner function of the motional state of a single trapped atom. Both of our measurement techniques rely on our ability to coherently displace the input state to several different locations in phase space. The technical realization of the displacements is described in the previous section in the context of the production of Schrödinger cat states. After the coherent displacement, we apply radiation on a motional sideband of the internal state transition for a time τ, which induces a resonant exchange between the motional and internal degrees of freedom. For each coherent displacement characterized by a complex number α, a time series of

measurements of the population $P_1(\alpha,\tau)$ is made by monitoring the fluorescence produced in driving the resonant dipole cycling transition. We repeat these measurements for several magnitudes and phases of the coherently displaced state and are able to extract information about the off-diagonal elements of the density matrix and can also reconstruct the Wigner function [13].
As an example of a reconstructed number state density matrix, we show in Fig. 1 our result for a coherent superposition of $|n=0\rangle$ and $|n=2\rangle$ number states. This state is ideally suited to demonstrate the sensitivity of the reconstruction to coherences. Our result indicates that the prepared motional states in our system are very close to pure states. However, by waiting a variable time, we can see the effects of decoherence as indicated by the disappearance of the off diagonal terms. Such experiments are important as diagnostics on the technical factors which limit the ability to create ideal entangled states.

B.4 New ion traps

An elongated version of our first single-ion trap has been completed and is now under final assembly. This trap is designed to trap a few ions (in a linear array) and perform quantum logic on them. The design philosophy has been to make minimal changes in trap technology (from the single ion trap) to achieve this goal.

We have refined the techniques for constructing miniaturized ion traps, and we now have a trap built and ready to be used in an experiment that is currently being assembled. There are four important steps involved in construction of this trap:

(1) Micromachining of the alumina substrates. Laser machined alumina substrates form the basic trap structure. We then use a phosphoric acid etch to further improve the smoothness of the machined edges.

(2) Substrate metallization. We first use a screen printing and high temperature firing technique to apply thick film Au contact pads for the wires leading from the trap. We then developed a silicon shadow mask that is a negative image of the circuit patterns on the substrates. We use this mask to apply a thin Ti adhesion layer (10 nm) and then a thick Au layer (300 nm) by electron beam evaporation.

(3) Surface mount bonding. We use parallel gap welding to attach the RC filter components to the substrates. We found that this technique can generate micro-fractures of the substrates, and we determined that this was due to sudden thermal expansion during the welding. With this knowledge, we were able to avoid any serious cracks in the substrates, and we have made design changes that will eliminate this problem in future versions of these traps.

(4) Substrate bonding. After all components are spot welded to the substrates, we then bond two substrates together with a 175 micrometer spacer using a fired silver paste as the bonding agent. We have assembled several traps, and presently we have one trap that is complete and ready to trap ions. The vacuum apparatus for this trap is currently being assembled, and we expect to test this system by the end of the summer.

B.4 Study of limitations and additional uses of ion trap quantum state synthesis

We have completed (and submitted to Reviews of Modern Physics) a paper which examines methods for, and practical limitations to, quantum state synthesis and quantum logic based on trapped atomic ions. We have examined several possible decohering mechanisms and have attempted to identify the most important of these. Current (single ion) experiments are limited by heating of the ion motion which we believe is caused by, as yet undetected, sources of injected noise. Strategies for resolving this issue in future experiments are described.

More fundamentally, we believe that the fidelity of logic operations will be limited by the effects of the 3L-1 "extraneous" motional modes of L trapped ions. These effects include (1) off-resonant excitation of the extraneous modes, (2) cross-mode coupling, and (3) fluctuations in the rates of logic operations due to thermal excitation of these extraneous modes. Various strategies are investigated including cooling all modes to the zero point and the possibility of multiplexing using small numbers of ions in parallel accumulators.

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